

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau



(43) International Publication Date
13 December 2001 (13.12.2001)

PCT

(10) International Publication Number
WO 01/95434 A1

(51) International Patent Classification⁷: H01Q 15/00,
13/10, 9/04

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(21) International Application Number: PCT/US01/17872

(22) International Filing Date: 1 June 2001 (01.06.2001)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
60/209,156 2 June 2000 (02.06.2000) US

(81) Designated States (*national*): AE, AG, AL, AM, AT, AU,
(utility model), AU, AZ, BA, BB, BG, BR, BY, BZ, CA,
CH, CN, CO, CR, CU, CZ, CZ (utility model), DE, DE
(utility model), DK, DK (utility model), DM, DZ, EC, EE,
EE (utility model), ES, FI, FI (utility model), GB, GD, GE,
GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ,
LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN,
MW, MX, MZ, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI,
SK, SL, TJ, TM, TR, TT, TZ, UA, UG, UZ, VN, YU, ZA,
ZW.

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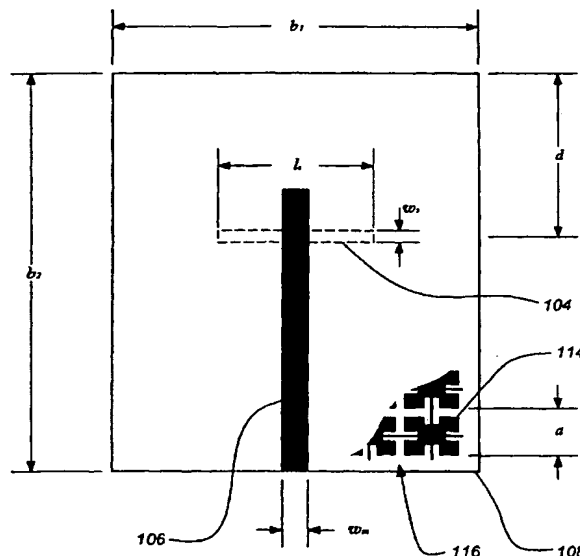
(84) Designated States (*regional*): ARIPO patent (GH, GM,
KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZW), Eurasian
patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European
patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE,
IT, LU, MC, NL, PT, SE, TR), OAPI patent (BF, BJ, CF,
CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG).

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Published:
— with international search report

[Continued on next page]

(54) Title: LOW-PROFILE CAVITY-BACKED SLOT ANTENNA USING A UNIPLANAR COMPACT PHOTONIC BAND-GAP SUBSTRATE



(57) Abstract: A low-profile cavity-backed slot antenna is disclosed including a cavity substrate having a slot with a resonant frequency and a uniplanar compact photonic band-gap (UC-PBG) substrate proximate to the cavity substrate and having a two-dimensional periodic metallic pattern on a dielectric slab and a ground plane, wherein the UC-PBG substrate behaves substantially as an open boundary at the resonant frequency of the slot. The slot antenna has reduced height while maintaining good performance.



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before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments

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**LOW-PROFILE CAVITY-BACKED SLOT ANTENNA
USING A UNIPLANAR COMPACT PHOTONIC BAND-GAP SUBSTRATE**

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims the benefit under 35 U.S.C. §119(e) of co-pending and commonly assigned U.S. Provisional Patent Application Serial Number 60/209,156, filed on June 2, 2000, by Tatsuo Itoh, Yongxi Qian, and Fei-Ran Yang, entitled "LOW-
5 PROFILE CAVITY-BACKED SLOT ANTENNA USING A UC-PBG SUBSTRATE," and attorney's docket number 30435.93USP1, which application is incorporated by reference herein.

**STATEMENT REGARDING FEDERALLY-SPONSORED
10 RESEARCH OR DEVELOPMENT**

This invention was made with Government support under Grant No. DAAH04-96-1-0005, awarded by the Army. The Government has certain rights in this invention.

BACKGROUND OF THE INVENTION

15 1. Field of the Invention

The present invention relates to cavity-backed slot antennas, and particularly to low-profile cavity-backed slot antennas using a uniplanar compact photonic band-gap substrate.

20 2. Description of the Related Art

Cavity-backed slot (CBS) antennas have been extensively investigated for applications to airborne and satellite communications, because they satisfy the requirements of flush mounting, low cost and light weight. The cavity height is usually designed to be one-quarter wavelength or three-quarters of a wavelength at the resonator
25 frequency in order not to destroy impedance matching, since the backing conductor is transformed to an open circuit in shunt with the slot. The cavity volume can be reduced through dielectric loading, but the bandwidth and efficiency will also be reduced.

Applications of photonic band-gap (PBG) materials to antennas have been presented for leakage modes suppression. Recently proposed uniplanar compact PBG (UC-PBG) structures exhibit a distinctive stopband and have been exploited to reduce surface wave of patch antennas.

5 There is a need in the art for low-profile flush-mounting antennas for airborne and satellite applications. There is further a need in the art for cavity-backed slot antennas with reduced cavity volumes, and particularly with low profile cavities, but without a loss of efficiency. There is further a need in the art for such low-profile cavity-backed slot antennas but without diminished bandwidth. The present invention meet
10 these needs.

SUMMARY OF THE INVENTION

To minimize the limitations in the related art described above, and to minimize other limitations that will become apparent upon reading and understanding the present
15 specification, the present invention discloses a low-profile cavity-backed slot antenna including a cavity substrate having a slot with a resonant frequency and a uniplanar compact photonic band-gap (UC-PBG) substrate proximate to the cavity substrate and having a two-dimensional periodic metallic pattern on a dielectric slab and a ground
20 plane, wherein the UC-PBG substrate behaves substantially as an open boundary at the resonant frequency of the slot. The substrate allows for a reduced cavity size while maintaining efficient antenna performance.

BRIEF DESCRIPTION OF THE DRAWINGS

Referring now to the drawings in which like reference numbers represent
25 corresponding parts throughout:

FIGS. 1A and 1B illustrate respectively an exploded schematic and cross section of a typical CBS antenna of the present invention using the UC-PBG substrate as a high-impedance reflector;

FIG. 2 illustrates detailed dimensions of the slot and microstrip for an example
30 cavity-backed slot antenna of the present invention;

FIGS. 3A and 3B illustrate respectively details of the UC-PBG substrate and detailed dimensions of the cell pattern for the example cavity-backed slot antenna of the present invention;

FIG. 4 is a plot of the insertion loss (S_{11}) of the example CBS antenna;

5 FIGS. 5A and 5B show respectively the measured normalized E-plane and H-plane radiation patterns for the example CBS antenna at 12.05 GHz; and

FIG. 6 illustrates the radiation patterns of a reference CBS antenna.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

10 In the following description of the preferred embodiment, reference is made to the accompanying drawings which form a part hereof, and in which is shown by way of illustration a specific embodiment in which the invention may be practiced. It is to be understood that other embodiments may be utilized and structural changes may be made without departing from the scope of the present invention.

15

Cavity-Backed Slot (CBS) Antenna

FIGS. 1A and 1B illustrate, respectively, an exploded schematic and a cross section of a typical CBS antenna 100 of the present invention using a UC-PBG substrate 102 as a high-impedance reflector. A slot 104 is center-fed by an open-ended microstrip 106 at the top layer of a cavity substrate 108, which is different from usual CBS antennas with slots at outer surfaces of cavities.

The present invention demonstrates a new type of CBS antenna 100 with a very thin cavity thickness, defined by the UC-PBG substrate 102 and any spacing layer (or the height of the slot 104 from the ground plane 110), such as the dielectric sheet 112. The UC-PBG substrate 102 is a dielectric substrate, grounded by the ground plane 110, loaded with a periodic metallic pattern (not shown), and serves as a reflector in the slot 104. This thin substrate 102 behaves like an open circuit boundary at a resonant frequency, and therefore good impedance matching condition of the microstrip-fed slot 104 is maintained. The thickness of the low-profile cavity, height of the slot 104 from the ground plane 110 is 35 mil ($\lambda_0/28$), which is much smaller than that of a reference antenna using an empty metal cavity with a thickness of 246 mil ($\lambda_0/4$). An example

antenna 100 is designed to operate at 12 GHz and the measured radiation patterns shows a front-to-back ratio of 15 dB, as well as low cross polarization levels.

The structure described is used to avoid perturbation of the microstrip 106 mode by the slot 104. The UC-PBG substrate 102 is maintained proximate to the cavity substrate 108. A dielectric sheet 112 is inserted between the slot 104 and the UC-PBG substrate 102, i.e., the high-impedance reflector, as a spacing layer. The slot 104 length and the distance between the microstrip 106 open end and the slot 104 center was initially designed as half- and quarter-wavelength, respectively, for the stand-alone slot antenna (comprising only the cavity substrate 108 with the slot 104 and the feeding microstrip 106) without considering the presence of the UC-PBG substrate 102. Optimizations of the slot 104 dimensions and the feeding microstrip 106 have been achieved using FDTD to simulate the entire structure. This FDTD analysis was then applied to simulate the CBS antenna 100 loaded with the UC-PBG substrate 102, wherein the dimensions of the slot 104 and the feeding microstrip 106 are adjusted as necessary to match the resonant frequency of the stand-alone slot antenna to that of the UC-PBG substrate 102.

FIGS. 2 and 3 illustrate detailed dimensions of an example CBS antenna 100 of the present invention. FIG. 2 illustrates detailed dimensions of the slot 104 and microstrip 106 for the example CBS antenna 100 of the present invention. The microstrip 106 on the top surface of the cavity substrate 108 has a width, w_m , and the slot 104 length and width are l_s and w_s , respectively. The cavity substrate 108 has overall dimensions of b_1 and b_2 and the slot 104 is offset from an edge of the cavity substrate 108 by a dimension, d . Beneath the cavity substrate 108, a cell 114 of the pattern 116 on the UC-PBG substrate 102 has a dimension, a .

FIGS. 3A and 3B illustrate respectively details of the UC-PBG substrate 102 and detailed dimensions of the cell pattern 116 for the example CBS antenna 100 of the present invention. The UC-PBG substrate 102 includes a two-dimensional metallic pattern 116 periodically etched on the surface of a grounded dielectric slab. Previous works show that there exists a complete stopband from 11 GHz to 14 GHz, meaning that no surface-wave or slab mode can be excited in that frequency range. The detail dimensions of the UC-PBG substrate 102 can be found in the publications: K. Ma, K.

Hirose, F. Yang, Y. Qian and T. Itoh, "Realization of magnetic conducting surface using novel photonic bandgap structure," *Electronics Lett.*, vol. 34, pp. 2041-2042, and in F. Yang, K. Ma, Y. Qian and T. Itoh, "A Novel TEM-Waveguide Using Uniplanar Compact Photonic Band-Gap (UC-PBG) Structure," *IEEE Trans. Microwave Theory*
 5 *Tech.*, vol. 47, pp. 2092-2098, Nov. 1999, all of which are incorporated by reference herein. The present invention utilizes another unique property of the UC-PBG substrate 102 (beyond the distinctive stopband), which is the realization of an equivalent open-circuit boundary at the resonant frequency.

In the present invention, the necessity of using a quarter-wavelength thick cavity
 10 is avoided by applying the periodic metallic pattern 116 loaded on a dielectric substrate 102 with a ground plane 108. Each cell 114 of this periodic pattern 116 provides inductances in shunt with capacitances. The combination of periodic loading and a shorted slab forms an LC tank, which behaves as an open circuit at a resonant frequency. The reflection coefficient of a uniform plane wave normally incident on the UC-PBG
 15 substrate 102 was simulated using finite-difference time-domain (FDTD) and the result showed a 180° phase difference compared to the reflection from a perfect electric conductor (PEC) at 13 GHz, indicating that an open circuit boundary was realized at the UC-PBG substrate 102 surface. This property has been verified by experiments and applied to build a transverse electro-magnetic (TEM) waveguide in the reference above.
 20 The periodic metallic pattern 116 of cells 114 is a unique two-dimensional periodic structure that comprises square pads 118 separated by capacitive gaps 120, and inductive lines 122 connecting adjacent cells 114. The dimensions, a , w_p , w_g , s , l_p and l_g define the example pattern 116 as shown in FIG. 3. The square pads have a side dimension, a , and the capacitive gaps have a dimension, s , and the inductive lines have a length, l_g .

25 By loading the UC-PBG pattern 116, the transformation from shorting plate to an open circuit at the air-dielectric interface is accomplished even for a thin slab. A low-profile CBS antenna 100 can be built using this thin UC-PBG substrate 102 as a backing substrate serving as a reflector without degrading the matching condition. A finite-difference time-domain (FDTD) method is used to design and analyze the proposed CBS
 30 antenna 100, which is then fabricated and measured to verify its usefulness.

Based on the full-wave simulation results, an example cavity-backed slot antenna 100 using the high-impedance reflector was manufactured with the following dimensions (units in mils): $b_1=2000$, $b_2=2100$, $l_1=400$, $w_1=20$, $w_m=90$, $d=700$, $a=120$, $w_p=40$, $w_d=10$, $l_p=27.5$ and $l_d=65$. The slot 104 and the 90 mil wide microstrip 106 feedline were built
 5 on an RT/Duroid 5870 TM cavity substrate 108 with dielectric constant of 2.33 and thickness of 31 mil. The spacing layer is a bare dielectric sheet 112 with dielectric constant of 2.33 and thickness of 10 mil. The UC-PBG substrate 102, used as the high impedance reflector, was fabricated on an RT/Duroid 6010 TM substrate with dielectric constant of 10.2 and thickness of 25 mil. The different layers of substrates were bonded
 10 together using dielectric paste with $\epsilon_r=2.16$ and $\tan\delta=0.001$. Copper tape was then used to enclose the side walls of dielectric layers.

Simulated and Experimental Results

Simulations and measurements have been conducted to obtain the reflection
 15 coefficient of the plane wave incident on the periodically loaded substrate. At certain frequencies, the reflection coefficient shows a 180 degree phase difference compared to that of the plane wave incident on a metal sheet, indicating that an open-circuit boundary has been realized. This phenomenon can be expected since the periodic metallic pattern 116 together with the grounded substrate 102 form a distributed LC circuit and the input
 20 impedance is infinite at the resonant frequency. Full-wave analysis also shows that there exists a complete stopband centering around the resonant frequency, where surface waves and slab modes cannot propagate. The periodically loaded substrate 102 can be used as a high-impedance reflector in a CBS antenna 100 to provide uni-directional radiation patterns and to maintain good impedance matching at the same time.

25 FIG. 4 is a plot of the insertion loss (S_{11}) of the example CBS antenna 100. The insertion loss was measured using an HP 8720A TM network analyzer and the result is shown in FIG. 4 together with the simulated S_{11} from the FDTD. The measured resonant frequency is 12.05 GHz and the 10 dB bandwidth is 5.8%. The trend of experimental data agrees well with simulation, except for the full-wave analysis predicting
 30 a higher resonant frequency since the effects of over-etching and dielectric paste were not taken into account.

FIGs. 5A and 5B show, respectively, the measured normalized E-plane and H-plane radiation patterns for the example CBS antenna 100 at 12.05 GHz. The front-to-back ratio is 15 dB for the E-plane and 18 dB for the H-plane patterns. The cross-polarization level is 12 dB to 15 dB below the co-polarization level for both planes. The pattern distortion observed in the E-plane comes from the existence of the microstrip 106 feed line and this problem can be alleviated using other feeding structures such as a coaxial line. The measured gain of this novel CBS antenna 100 is approximately 2.5 dB.

FIG. 6 illustrates the radiation patterns of a reference CBS antenna. The reference CBS antenna has been built using an empty metal cavity with the height equal to a quarter free-space wavelength (246mil). The comparison between the CBS antenna 100 of the present invention and the reference CBS antenna reveals that the CBS antenna 100 using the UC-PBG substrate 102 as a high-impedance reflector not only achieves the low-profile design but also provides good radiation patterns.

The problem of surface wave or slab mode excitation on the high-impedance reflector CBS antenna 100 of the present invention does not exist since the periodic structure 116 of the UC-PBG substrate 102 creates a complete stopband at the resonant frequency. The fabrication process requires only planar etching technique, which is very cost-effective. The dimensions of the high-impedance reflector 102 can be scaled to any other frequencies in order to match antenna resonant frequencies. The bandwidth of the CBS antenna 100 itself can be increased by optimizing the slot 104 width. Meanwhile, the bandwidth of the high-impedance reflector 102 can be enlarged by inserting more layers of periodic loading.

Conclusions

A low-profile CBS antenna 100 has been realized using the UC-PBG substrate 102 as a reflector, which behaves like an open-circuit boundary at a resonant frequency. The slot 104 height from the ground plane 110 is much smaller $\lambda_0/28$ (35mil) compared to a conventional slot antenna backed by a metallic cavity with thickness of $\lambda_0/4$ (246mil). Front-to-back ratio of 15dB and low cross-polarization level have been measured. Measured results of the novel CBS antenna 100 do not show degradation in the radiation performances compared to the reference antenna. The proposed CBS

antenna 100 is very easy to fabricate due to its planar feature and can be readily applied to CBS arrays, which are often used for satellite communications. This concept of using a UC-PBG substrate 102 as a backing cavity or reflecting plane can be extended to find more applications, such as CBS arrays, phased-array systems, and loop antennas.

5 In addition, many equivalent structures affording low profile cavities by using UC-PBG substrates 102 which produce an open circuit boundary at a resonant frequency will be apparent to those skilled in the art. Particularly, various equivalent patterns 116 of cells 114 on the UC-PBG substrate 102 may also be described for a range of resonant frequencies yielding substantially similar results.

10 This concludes the description including the preferred embodiments of the present invention. The foregoing description of the preferred embodiment of the invention has been presented for the purposes of illustration and description. It is not intended to be exhaustive or to limit the invention to the precise form disclosed. Many modifications and variations are possible in light of the above teaching.

15 It is intended that the scope of the invention be limited not by this detailed description, but rather by the claims appended hereto. The above specification, examples and data provide a complete description of the manufacture and use of the apparatus and method of the invention. Since many embodiments of the invention can be made without departing from the spirit and scope of the invention, the invention
20 resides in the claims hereinafter appended.

References

The following references are incorporated by reference herein:

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25 studies of cavity-backed slot antenna excited by a narrow strip," IEEE Trans. Antennas Propagat., vol. 41, pp. 236-241, Feb. 1993.
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6. R. Coccioli, F.R. Yang, K.P. Ma, and T. Itoh, "Aperture coupled patch antenna on UC-PBG substrate," IEEE Trans. Microwave Theory Tech, vol. 47, pp. 2123-2130. Nov. 1999.
- 10 7. K. Ma, K. Hirose, F. Yang, Y. Qian and T. Itoh, "Realization of magnetic conducting surface using novel photonic bandgap structure," Electronics Lett., vol. 34, pp. 2041-2042.
8. F. Yang, K. Ma, Y. Qian and T. Itoh, "A Novel TEM-Waveguide Using Uniplanar Compact Photonic Band-Gap (UC-PBG) Structure," IEEE Trans. Microwave
15 Theory Tech., vol. 47, pp. 2092-2098, Nov. 1999.
9. J. Kraus, Antennas, 2nd Ed, McGraw-Hill, 1988.

WHAT IS CLAIMED IS:

1. A cavity-backed slot antenna, comprising:
a cavity substrate including a slot having a resonant frequency; and
a uniplanar compact photonic band-gap (UC-PBG) substrate proximate
5 to the cavity substrate and having a two-dimensional periodic metallic pattern on
a dielectric slab and a ground plane;
wherein the UC-PBG substrate behaves substantially as an open
boundary at the resonant frequency of the slot.
- 10 2. The cavity-backed slot antenna of claim 1, further comprising a
dielectric sheet between cavity substrate and the UC-PBG substrate as a spacing
layer.
3. The cavity-backed slot antenna of claim 2, wherein the dielectric
sheet has a dielectric constant of approximately 2.33.
- 15 4. The cavity-backed slot antenna of claim 1, further comprising an
open-ended microstrip at a top surface of the cavity substrate, wherein the slot is
center-fed by the microstrip.
5. The cavity-backed slot antenna of claim 1, wherein the pattern
comprises repeating cells and each cell provides inductances in shunt with
capacitances to produce the open boundary at the resonant frequency.
- 20 6. The cavity-backed slot antenna of claim 5, wherein the cells
comprise square pads separated by capacitive gaps, and inductive lines connecting
adjacent cells.
7. The cavity-backed slot antenna of claim 6, wherein the square
pads have a side dimension, a , and the capacitive gaps have a dimension, r , and
25 the inductive lines have a length, l_d .

8. The cavity-backed slot antenna of claim 1, wherein the slot is formed in the cavity substrate on a side proximate to the UC-PBG substrate.

9. The cavity-backed slot antenna of claim 1, wherein the cavity substrate has a dielectric constant of approximately 2.33.

5 10. The cavity-backed slot antenna of claim 1, wherein a height of the slot from the ground plane is approximately $\lambda_0/28$.

11. The cavity-backed slot antenna of claim 1, wherein the resonant frequency is approximately 12.05 GHz.

10 12. The cavity-backed slot antenna of claim 1, wherein the dielectric slab of the UC-PBG substrate has a dielectric constant of approximately 10.2.

13. A method of producing a cavity-backed slot antenna, comprising:
providing a cavity substrate including a slot having a resonant frequency;
and

15 providing a uniplanar compact photonic band-gap (UC-PBG) substrate proximate to the cavity substrate and having a two-dimensional periodic metallic pattern on a dielectric slab and a ground plane;

wherein the UC-PBG substrate behaves substantially as an open boundary at the resonant frequency of the slot.

20 14. The method of claim 13, further comprising providing a dielectric sheet between cavity substrate and the UC-PBG substrate as a spacing layer.

15. The method of claim 14, wherein the dielectric sheet has a dielectric constant of approximately 2.33.

16. The method of claim 13, further comprising feeding the slot with an open-ended microstrip at a top surface of the cavity substrate.

17. The method of claim 13, wherein the pattern comprises repeating cells and each cell provides inductances in shunt with capacitances to produce the open boundary at the resonant frequency.

18. The method of claim 17, wherein the cells comprise square pads separated by capacitive gaps, and inductive lines connecting adjacent cells.

19. The method of claim 18, wherein the square pads have a side dimension, a , and the capacitive gaps have a dimension, s , and the inductive lines have a length, l_d .

20. The method of claim 13, wherein the slot is formed in the cavity substrate on a side proximate to the UC-PBG substrate.

21. The method of claim 13, wherein the cavity substrate has a dielectric constant of approximately 2.33.

22. The method of claim 13, wherein a height of the slot from the ground plane is approximately $\lambda_0 / 28$.

23. The method of claim 13, wherein the resonant frequency is approximately 12.05 GHz.

24. The method of claim 13, wherein the dielectric slab of the UC-PBG substrate has a dielectric constant of approximately 10.2.

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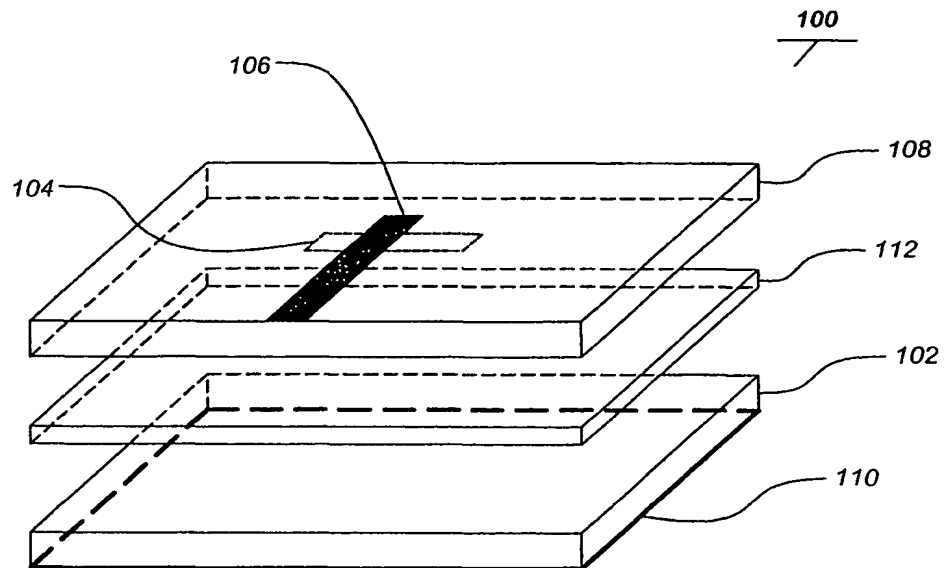


FIG. 1A

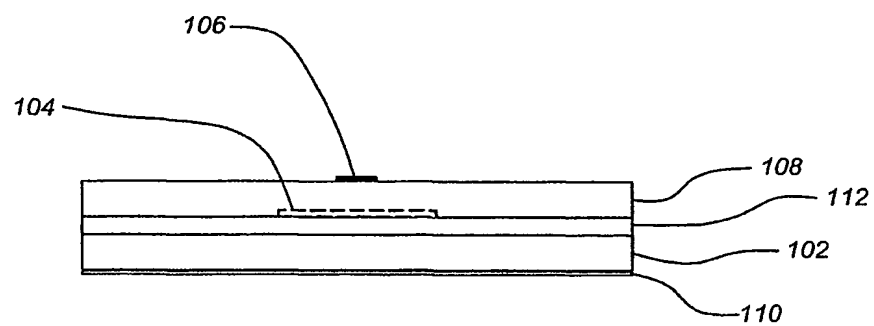


FIG. 1B

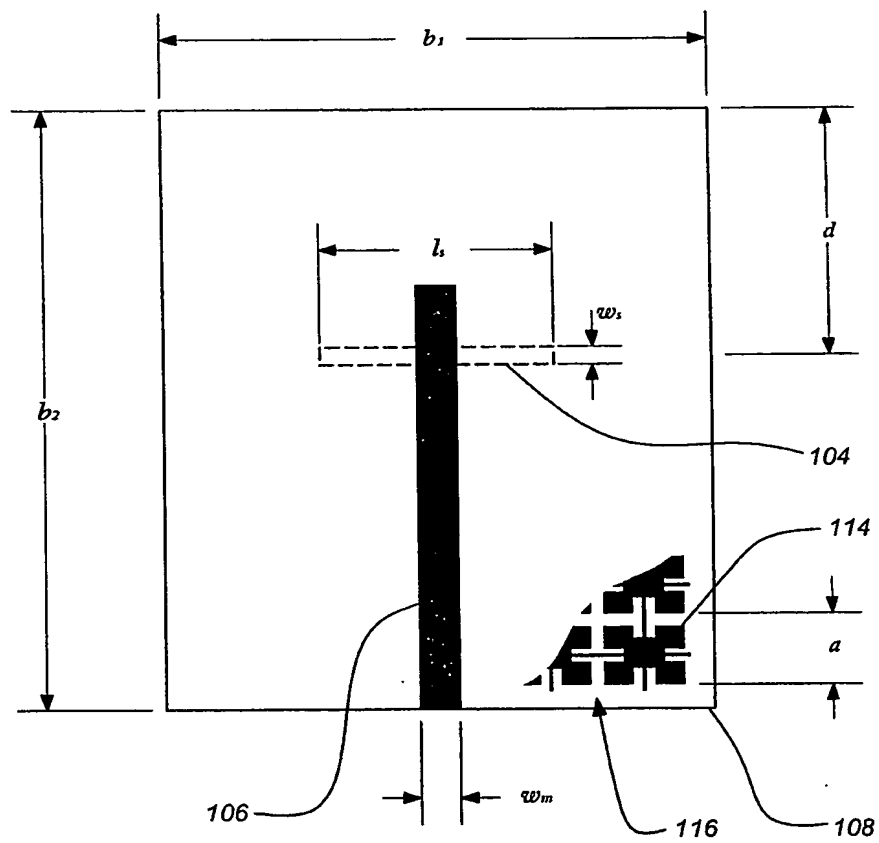


FIG. 2

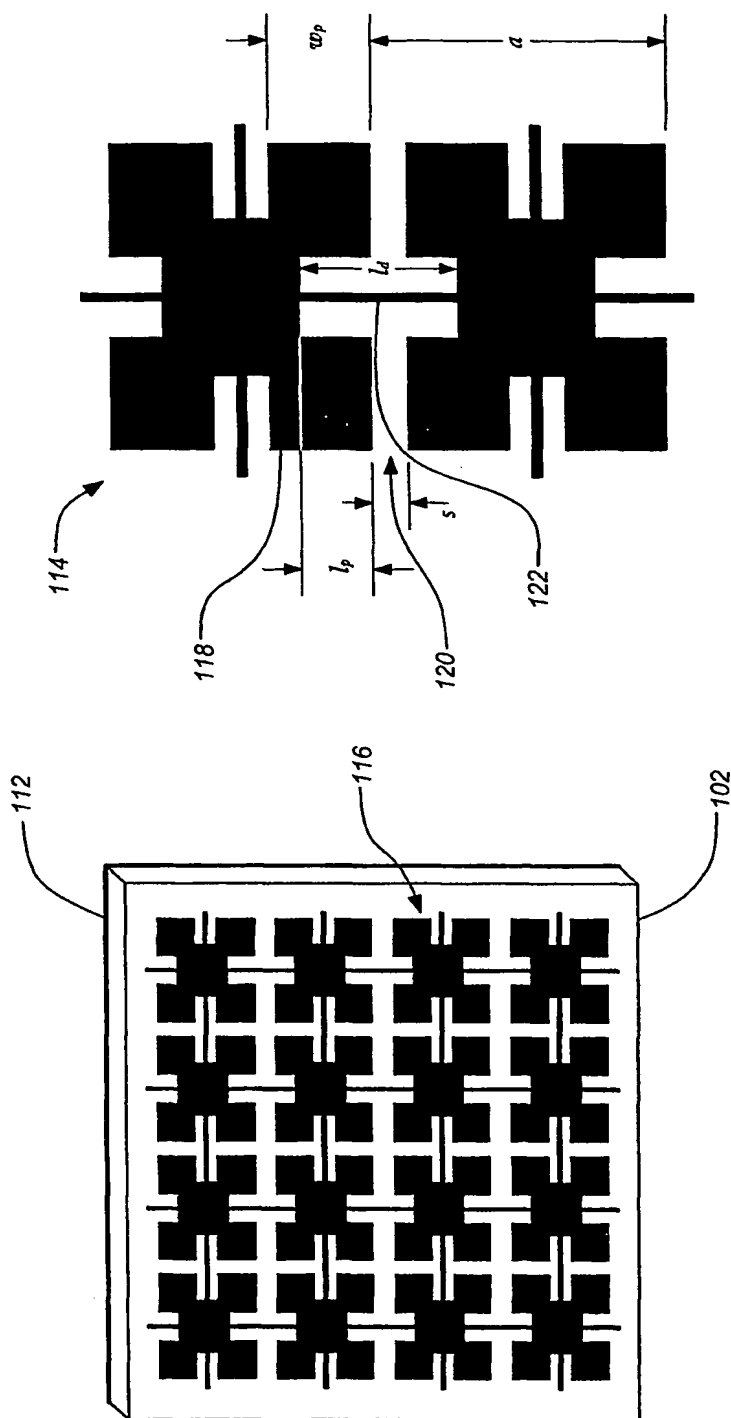


FIG. 3B

FIG. 3A

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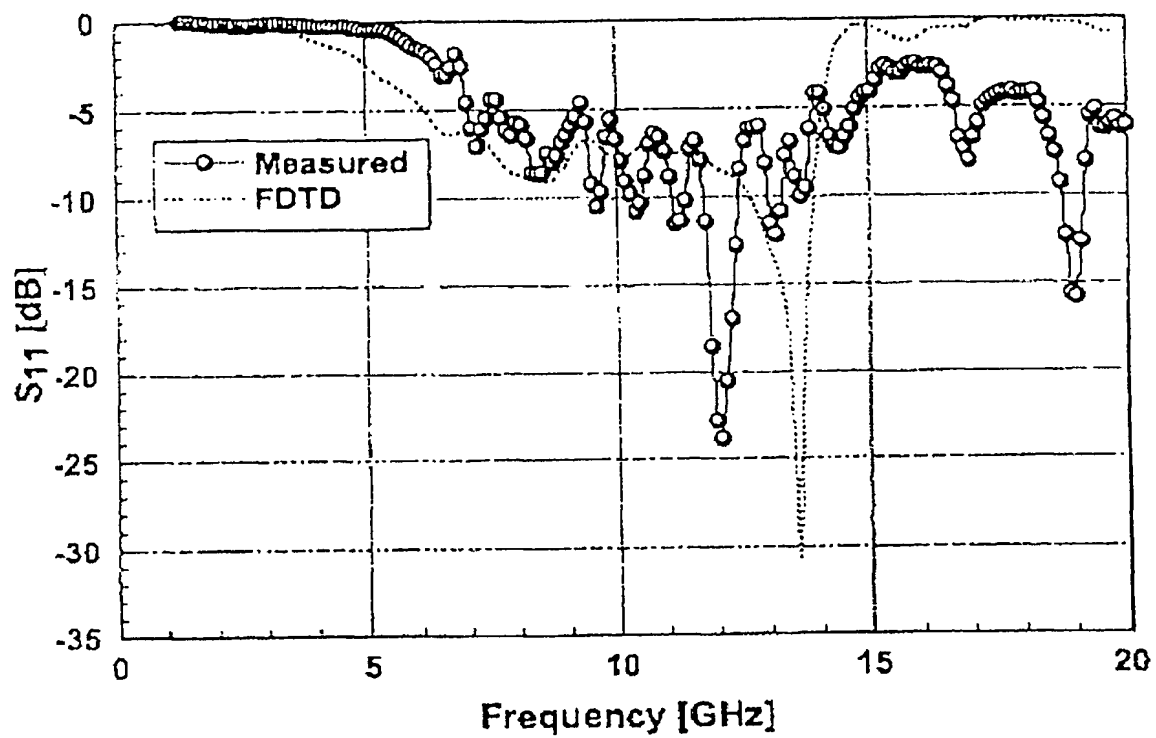
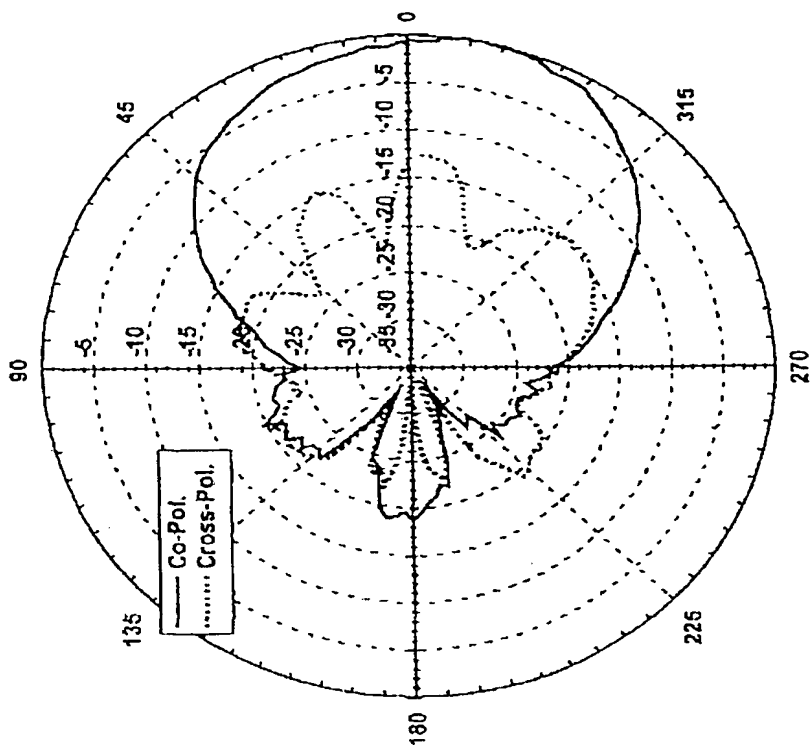


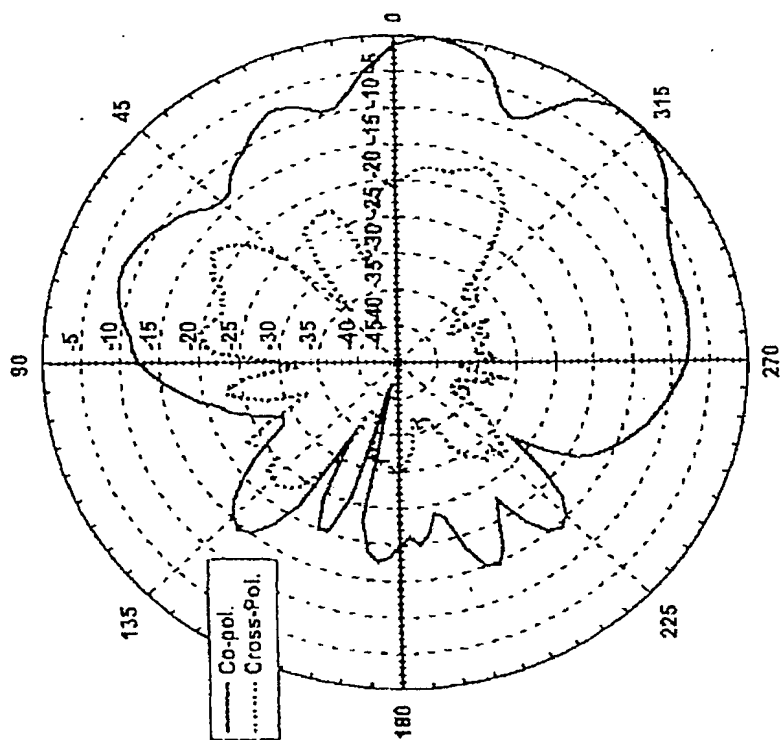
FIG. 4

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H-Plane

FIG. 5B



E-Plane

FIG. 5A

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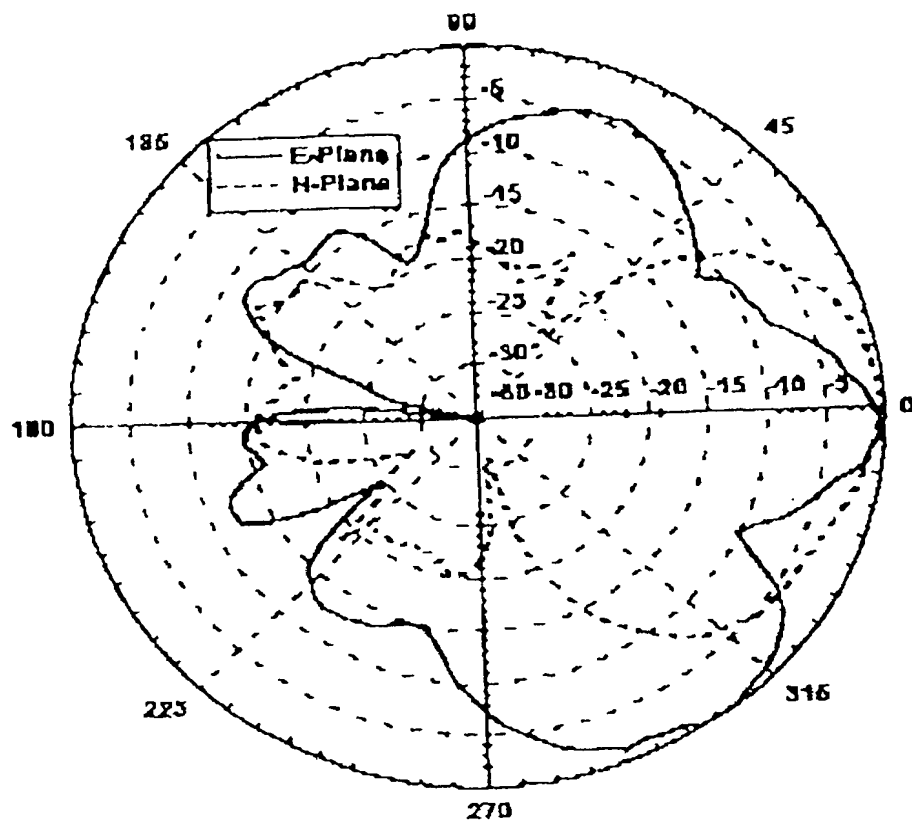


FIG. 6

INTERNATIONAL SEARCH REPORT

Int. Application No
PCT/US 01/17872

A. CLASSIFICATION OF SUBJECT MATTER

IPC 7 H01Q15/00 H01Q13/10 H01Q9/04

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 7 H01Q

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the International search (name of data base and, where practical, search terms used)

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C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	SHUMPERT J D ET AL: "PARALLEL-PLATE MODE REDUCTION IN CONDUCTOR-BACKED SLOTS USING ELECTROMAGNETIC BANDGAP SUBSTRATES" IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, IEEE INC. NEW YORK, US, vol. 47, no. 11, November 1999 (1999-11), pages 2099-2103, XP000865107 ISSN: 0018-9480 cited in the application page 2100, right-hand column, line 31 - line 45 page 2101, left-hand column, line 7 - line 20; figures 1,3 --- -/--	1,4-13, 16-24



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Moumen, A

INTERNATIONAL SEARCH REPORT

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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	<p>COCCIOLI R ET AL: "APERTURE-COUPLED PATCH ANTENNA ON UC-PBG SUBSTRATE" IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, IEEE INC. NEW YORK, US, vol. 47, no. 11, November 1999 (1999-11), pages 2123-2130, XP000865110 ISSN: 0018-9480 cited in the application page 2124, left-hand column, line 25 - line 39; figures 1,2</p>	1,5-7, 13,17-19
A	<p>SHAHROKH HASHEMI-YEGANEH ET AL: "THEORETICAL AND EXPERIMENTAL STUDIES OF CAVITY-BACKED SLOT ANTENNA EXCITED BY A NARROW STRIP" IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, IEEE INC. NEW YORK, US, vol. 41, no. 2, 1 February 1993 (1993-02-01), pages 236-241, XP000303633 ISSN: 0018-926X cited in the application page 236, right-hand column, line 18 - line 27; figure 1</p>	1,4,13, 16
A	<p>MOYER H P ET AL: "ACTIVE CAVITY-BACKED SLOT ANTENNA USING MESFET'S" IEEE MICROWAVE AND GUIDED WAVE LETTERS, IEEE INC, NEW YORK, US, vol. 3, no. 4, 1 April 1993 (1993-04-01), pages 95-97, XP000358562 ISSN: 1051-8207 page 95, left-hand column, line 24 - line 35 page 95, right-hand column, line 22 - line 34; figure 1</p>	1,13